Appendix I


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View of refuge

A Geomorphological Analysis of the Monomoy Barrier System

Provincetown
Center for Coastal Studies

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by

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1. PREFACE

This report is submitted at the request of the Eastern Massachusetts National Wildlife Refuge Complex for geomorphological research and report preparation in support of a comprehensive conservation plan for Monomoy National Wildlife Refuge. Areas of interest specified include a summary of the present understanding of outer Cape Cod coastal processes; a chronology of southeastern Chatham coastal forms using aerial photographs to illustrate changes at Monomoy; a general overview of climate change and associated sea level rise with respect to the study area; discussion of the potential benefits and problems associated with dredging around Monomoy; and discussion of potential future research to benefit Refuge management.

2 . INTRODUCTION

"Monomoy" as seen on regional maps appears as an appendage to the bended arm of Cape Cod, extending southward some 15 km. from the Cape's sharp elbow at Morris Island in Chatham (e.g., Fig. 1). Depending on the map's date, Monomoy may have the form of a continuous peninsula – a barrier spit consisting of dunes, marshes and beaches with a bulbous terminus at Monomoy Point, or it may appear as a series of isolated and small barrier islands and shoals in the north leading southward to a larger island, "South Monomoy Island". However, the marine setting is similar at all dates: Monomoy is bordered on the southeast by a northeast-southwest trending channel, "Pollock Rip Channel"; on the southwest by a string on shoals known collectively as "Handkerchief Shoal" parts of which are sometimes exposed at extreme low water; and on the west by a broad shallow triangular platform, "Monomoy Flats" (Fig. 1).

3. METHODOLOGY

Cartography. Studies of the Monomoy Barrier Beach System using comparative cartographic sources began in earnest in 1871 with the work of Henry Mitchell. Mitchell, a prominent scientist and accomplished topographer with the Coast Survey, relied on the accurate field work and charts of the Coast Survey to document the movement and growth of the Monomoy

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Spit and its offshore shoals and to investigate the potential effect of this movement on maritime commerce (Mitchell, 1871; Mitchell, 1873; Mitchell, 1874; Mitchell, 1886; and Mitchell, 1887). This present study, employing a similar methodology of chronological cartographic and aerial photograph comparisons, continues work undertaken for the Chatham Conservation Commission more than 30 years ago on the Nauset Beach System (Giese, 1978, Giese et al., 1989).

A major goal of the present study was to develop and document a chronology of the changing form of the Monomoy barrier beach system. To help achieve this goal, methodology from the Massachusetts Office of Coastal Zone Management (CZM) Historical Shoreline Mapping Project (Mapping Project) was adapted to meet the specific requirements of the current work. The Mapping Project, completed in 2007, evaluated historical cartographic documents from the 17^{th} century through the present to establish presumptive lines of state tidelands jurisdiction for the entire coast of Massachusetts (Mague & Foster, 2008) and the methodology used to assess and apply historical cartographic documents in a contemporary mapping context is well-documented (BSC, 2007).

The methodology of this current study is based on a six-step approach: (1) research of cartographic and archival information depicting onshore and offshore historical configurations of the Monomoy barrier beach system; (2) qualitative assessment of historical information, including maps, charts, plans and narratives, to identify documents for further consideration; (3) registration of cartographic information to the North American Datum of 1983 (NAD83); (4) analysis and assessment of registered maps and charts with verifiable spatial accuracies; (5) digitization of topographic and bathymetric barrier beach features representing the location of salt marsh, mean high water (MHW) lines, mean low water (MLW) lines, and 1-, 2-, and 3-fathom lines for the following time frames: 1853-54, 1873-74, 1886-89, 1902, 1931, 1979, and 1996; and (6) compilation of figures depicting the location of these barrier beach features for each period to facilitate a comparative analysis.

As a recognized authority for the location of historical coastal features (Shalowitz, 1964), the work of the U.S. Coast Survey and in particular the information recorded on its topographic (T-sheets) and hydrographic (H-sheets) field sheets form the basis of the chronological series of figures and cartographic comparisons considered in this study.[1] Period-specific nautical charts, where necessary, were used to clarify cartographic symbology on T- and H-sheets and to fill in gaps in spatial coverage.

The horizontal accuracies of T- and H-sheets are well documented and quantifiable, making them well-suited for historical studies (Mague, 2009). When T-sheets and H-sheets are registered using archived coordinate values for Coast Survey triangulation stations (Coast Survey, 1851; Coast and Geodetic Survey, 1894) or sheet graticules translated to the project datum in accordance with accepted procedures (BSC, 2007), they have been shown to meet or exceed National Map Accuracy Standards at their respective compilation scales (BSC, 2007; Daniels & Huxford, 2001; Crowell et al, 1991). Estimates of H-sheet accuracies, with horizontal and vertical components, are more difficult to quantify. Referenced to local MLW datums frequently defined relatively short series of tidal measurements, H-sheet sounding accuracies have been estimated to range from 3 to 4± feet for 1800s to early 1900s surveys, 2 to 3± feet for mid-1900s surveys, and 0.5 to 1.0± feet for modern surveys (Byrnes, 2002; Johnston, 2003; and U.S. Coast Survey, 1878). For shallow depths (± 15 feet), small tidal ranges, and regular bottoms with minimal relief, such as much of the area surrounding Monomoy, these estimates would appear to be conservative. Future work that includes refining these uncertainties is necessary for a detailed assessment of the sediment transport systems, nearshore and offshore processes, and the calculation of sediment budgets and volumes that contribute to the formation of the extensive shoals surrounding Monomoy, particularly the triangular area extending approximately 2 miles to the west, characterized by flat relief, a tidal range of 3 ± feet, and a significant shoal area defined by the 1-, 2-, and 3-fathom lines. (Note: 1 fathom = 6 feet).

[1] The official name of the U.S. Coast Survey has evolved over time. Reference to the Coast Survey throughout this report is meant to include the U.S. Coast Survey and its successor agencies the U.S. Coast & Geodetic Survey and the current Office of Coast Survey.

Copies of the historical plans of the U.S. Coast Survey were obtained from the digital database of the Mapping Project, which contains in excess of 2,600 historical plans, maps, and charts of the Massachusetts coast (BSC, 2007). Historical charts were obtained from the Historical Map & Chart Project website of the National Oceanic & Atmospheric Administration (NOAA) Office of Coast Survey. Contemporary charts of the area were obtained from the NOAA Office of Coast Survey Nautical Charts website. A list of all historical and contemporary cartographic information considered for this study is contained in Section 11.

Information from historical and contemporary maps, charts, sketches, and orthophotos were incorporated into a project Geographic Information System (GIS), created in ArcGIS 9.3 with MassGIS, 1:5,000 scale, 2005 orthophotos as the base map, to develop figures depicting the shape and orientation of Monomoy Spit and its nearshore bathymetry out to a depth of three fathoms (18 feet), local MLW datum. Historical cartographic manuscripts were registered to the North American Datum of 1983 (NAD83) using the ESRI, ArcGIS 9.3 georeferencing extension, set for a First Order Polynomial (Affine) Transformation. Registration points consisted of Coast Survey triangulation stations or map graticules with a minimum of six points retained for each registration with the goal of minimizing the root mean square (rms) of the error associated with the registration or control points. To the extent possible, registration points were distributed equally across each manuscript to account for potential unequal distortion of the source document.

Finally, similar to the approach of Mitchell, figures depicting the historical positions and spatial orientation of Monomoy and its offshore shoals were compiled at the same scale to facilitate qualitative comparisons of geomorphic changes over the past 160 years. These figures are presented in Section 5.

Photography. A review of historic aerial photographs was completed at the Cape Cod National Seashore (CCNS) collection, and the Barnstable Service Center of the U.S. Department of Agriculture's Natural Resources Conservation Service (USDA/NRCS) office. Printed photos that cover Monomoy from 1938 and 1960 were located at the CCNS. The 1938 set does not extend northward to the southeastern shore of Chatham. A set of 1978 aerial photos ends in Chatham; it does not extend southward to include Monomoy. A set of 1947 photos also stopped in Chatham for the printed copies of the CCNS collection, however, additional photos in this series are available and could be incorporated in to future analyses.

Black and white aerial photos available from USDA/NRCS are 1938, 1951, 1971 and 1980. A set of color infrared photos are available for 1984. Orthorectified aerial photographs were available in digital format for 2009 from the Town of Chatham. A 2002 orthophoto was provided by the Town of Chatham, which was acquired by the National Fish and Wildlife Service. Additional orthorectified aerial photos were available for 1994, 2001 and 2005 from the Massachusetts state office of Geographic Information Systems (MassGIS).

Year	Description	Source Location	Comments
1938	**B & W**	**NPS and NRCS/USDA**	**scanned and mosaiced, used for interpretation**
1947	B & W	NPS/Aerial Viewpoint	available for purchase, may be useful for future study
1951	B & W	NRCS/USDA	reviewed, may be useful for future study
1960	**B & W**	**NPS Highland Lab**	**scanned and mosaiced, used for interpretation**
1971	B & W	NRCS/USDA	reviewed, may be useful for future study
1980	B & W	NRCS/USDA	reviewed, very small scale probably not useful
1984	CIR	NRCS/USDA	reviewed, may be useful for future study
1991	B & W paper	Town of Chatham	scanned and mosaiced
1994	**Orthophoto**	**MassGIS**	**digital files used for interpretation**
1997	B & W paper	Town of Chatham	scanned and mosaiced
2001	Orthophoto	MassGIS	digital files used for interpretation
2002	Orthophoto	DFW/Town of Chatham	digital files used for interpretation
2005	**Orthophoto**	**MassGIS - Coastal**	**digital files used for interpretation**
2009	**Orthophoto**	**Town of Chatham**	**digital files used for interpretation**

Table 1 Summary of Aerial Photo Review

Blue text denotes aerial photos used in this report. Aerial photos in green text were acquired but not utilized for this study. Black text denotes other photos that are available for the study area.

The scanned aerial photos for 1938, 1960, 1991 and 1997 were cropped and compiled in Adobe Photoshop, because there were not enough common features through time to georeference each photo frame given the dynamic nature of Monomoy. Once the photos were compiled into a montage for each year they were aligned generally in ArcView 9.3 using the georeferencing toolbar resizing and adjustment tools. There were not enough common points evenly

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distributed throughout the different time series to rectify the photos with common tie points. However, the general adjustment did allow for a basic alignment of the photos for comparison and scaling purposes.

4. REVIEW OF GEOMORPHOLOGICAL HISTORY

The genesis of Monomoy as the southern extremity of a 34 km deposition feature beginning at Coast Guard Beach in Eastham, the "Nauset-Monomoy Barrier System", has been treated in detail by Goldsmith (1972). In brief, the system is a complex of barrier beaches, barrier spits, barrier islands and associated tidal inlets consisting of sediment initially supplied by the erosion of glacial deposits exposed along the 32 km-long line of east-facing cliffs and nearshore sea bed that extends northward from Eastham to North Truro.

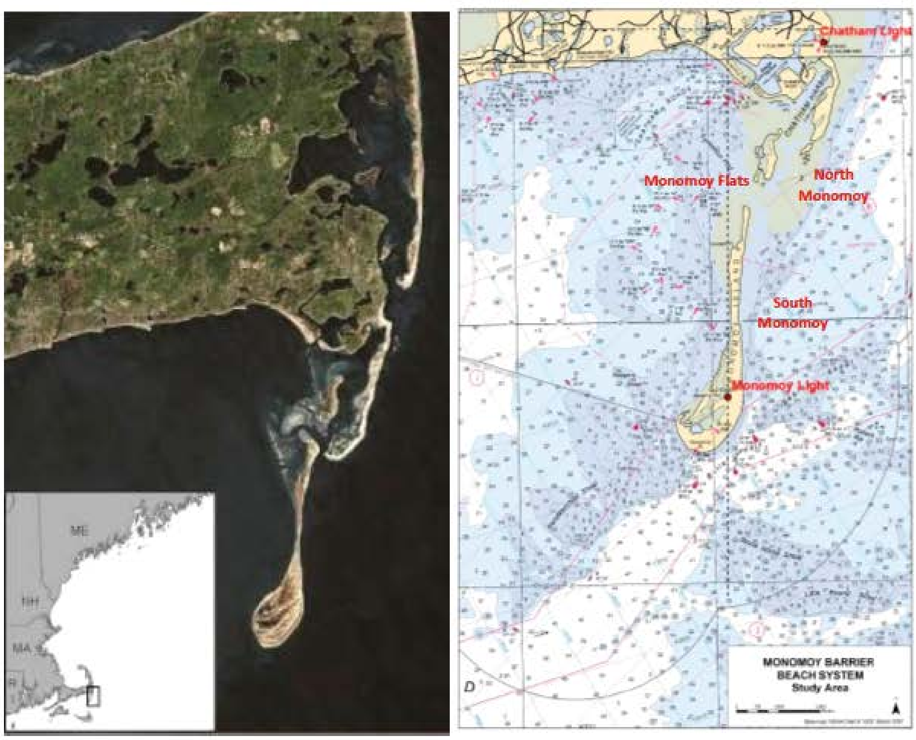

FIGURE 1

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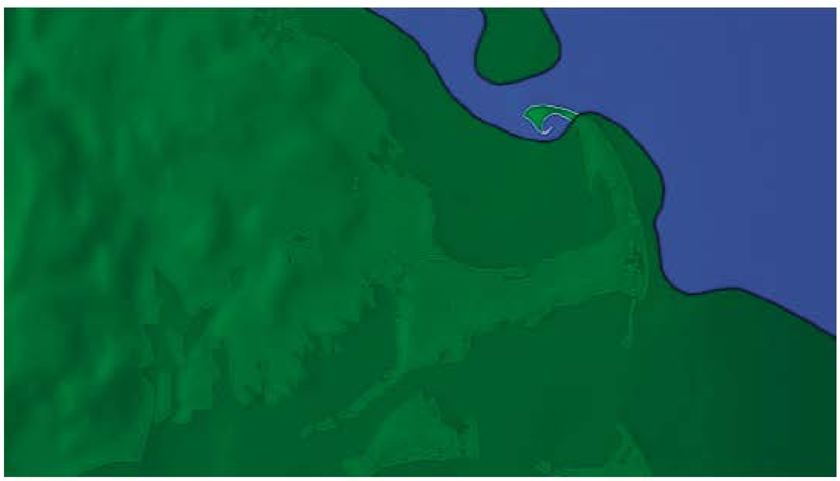
Early Holocene. As discussed in Section 5, historical geomorphic changes at Monomoy occur in step with those of Nauset Beach, however, before examining these processes in detail, let us review the broader scale development of the Cape Cod landmass during the Holocene Period – the approximately 12,000 year period following the most recent ("Wisconsin" stage) glaciation. At that time, sea level was some 55 m below its present level and most of the area comprising present-day Cape Cod Bay, Cape Cod, Nantucket Sound and Nantucket, and Vineyard Sound and Martha's Vineyard was part of the terrestrial borderland of the continental margin (Fig. 2).



Adapted from Uchupi, *et al.* 1996

FIGURE 2

The early Holocene was a period of rapid sea level rise. By 6,000 years B.P. (before present), sea level had risen some 45 m and was approximately 10 m below its present level. As a result of this submergence, the Cape and Islands, with their bays and sounds, became fully differentiated (Fig. 3), however, the major depositional features of outer Cape Cod, Provincetown Hook, Nauset Beach and Monomoy had not yet formed.

Adapted from Uchupi, *et al.* 1996

FIGURE 3

<u>*Late Holocene*</u>. Wave-driven sediment transport became the major process controlling shoreline evolution during the past 6,000 years. At the beginning of this period, George's Bank - until that time a gradually shrinking landmass between Cape Cod and the open Atlantic basin – became fully submerged. As a result, higher energy, open ocean waves - previously highly damped by the time they reached the coast – were capable of transporting increased amounts of sediment. According to Uchupi et al. (1996), glacial sediments eroded from the sea cliffs and nearshore bottom between North Truro and Eastham during this time period were responsible for the construction of Provincetown Hook to the north and the Nauset-Monomoy barrier system and Handkerchief Shoals to the south.

Notably, the rate of shoreline retreat accompanying these changes increased southward. Between about 6,000 and 1,000 years ago, the eroding bluff section retreated at an average rate of approximately 0.3 m/year at the northern end and 0.6 m/year in the south (Uchupi et al., 1996). A recent study (Giese and Adams, 2007) reports that contemporary century-scale bluff retreat rates continue to increase north-to-south by a factor of two, but the contemporary rates (ranging from 0.5 m/year to 1.0 m/year) are greater in magnitude, perhaps a response to acceleration in the rate of sea level rise. Presently on-going research indicates that the southward increase in coastal retreat continues southward, past the end of the bluff section and along the length of Nauset Beach at least as far south as North Chatham. There, the century-scale average retreat exceeds 1.5 m/year, 3 times the retreat rate of the north end of the bluff section (Vaux, in press). Many local anecdotal reports confirm continual westward migration of Nauset Beach during the historical period (e.g., Nickerson, 1988).

If we assume, based on these rates of coastal retreat, that Nauset Beach lay 1 to 2 km offshore of its present location a thousand years ago, it seems unlikely that the origin of Monomoy predates that time. Geological maps of Cape Cod (e.g., Oldale and Barlow, 1986) indicate "ice contact" glacial deposits west of the northern section of Nauset Beach, and Uchupi et al. (1997) propose that the original eastern boundary of glacial Cape Cod lay just eastward of the present upland coasts of Nauset Harbor, Pleasant Bay, and Chatham Harbor. In that case, a long marine embayment lay inside Nauset Beach at 1,000 years BP, extending from the Eastham upland southward to the vicinity of Chatham.

Presently restricted basins such as Pleasant Bay, Little Pleasant Bay, and Nauset Harbor would have had free access to the embayment, while the embayment would have had a relatively unrestricted connection with the sea. Given this configuration, southward moving littoral sediment would not have reached the upland coast of south Chatham as it does today.

Recent history. By the time that accurate maps of the coast became available (e.g., Des Barres, 1764), Nauset Beach had migrated far enough westward to severely restrict tidal flow in the narrowing embayment. Even earlier (17^{th} Century) sketches and notes by Champlain (1607) (Fig. 4) suggest that Nauset Harbor was already largely tidally-separated from the Pleasant Bay system to the south. The restriction of tidal flow between the Pleasant Bay basins and the open sea produced by changes in Nauset Beach have produced a quasi-cyclic pattern of tidal inlet/barrier island formation and barrier spit development (e.g., Mitchell, 1873; Goldsmith, 1972; Giese, 1978). In brief, this pattern consists of the following steps: 1) a breach in Nauset

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Beach, 2) southwest migration of the southern barrier island (i.e., detached south end of Nauset Beach), 3) Nauset Beach elongation to the south, followed by, 4) a new breach.

Champlain, 1607

FIGURE 4

It is the second step of this pattern that concerns us here because an analysis of historical shoreline changes in the Monomoy region indicates that the detached end of Nauset Beach is the major sediment source for landforms in that region. As can be seen in Figure 5, adopted from a recent report by (Giese et al., 2009), following initiation of a new inlet referred to as "North Inlet" (Fig. 5b,) the former inlet ("South Inlet") closes (Fig. 5c) enabling littoral transport of sediment southward from the barrier island ("South Beach") to Monomoy.

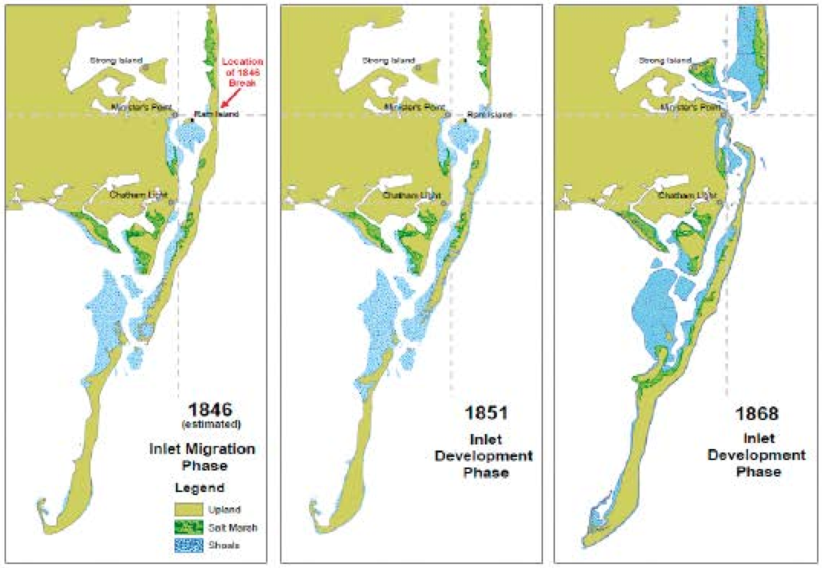

FIGURE 5 (a, b, c)

As the result of southward and westward sediment transport over the following decades (Figs. 6 and 7), Monomoy shifts westward, widens, attaches to Morris Island, and grows southward. After about a century, southward-growing Nauset Beach overlaps North Monomoy, which is deprived of incoming sediment, and begins to break-up into a group of islets and shoals. Finally, when Nauset Beach breaches again, and a new "South Beach" attaches to South Monomoy Island, a renewed sediment supply is available to nourish South Monomoy (Fig. 8c).

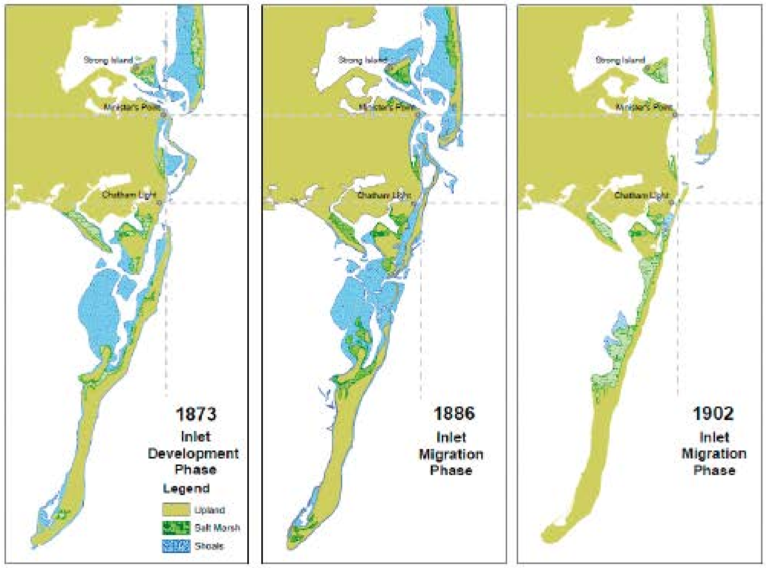

FIGURE 6 (a, b, c)

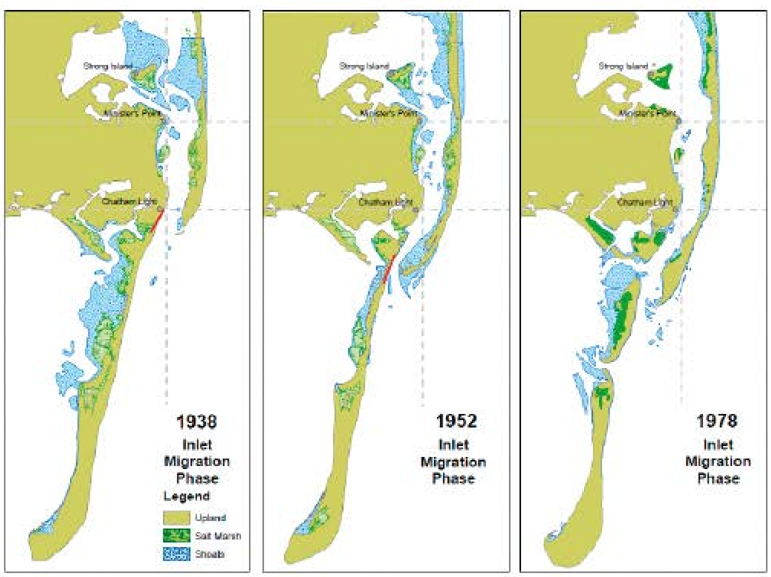

FIGURE 7 (a, b, c)

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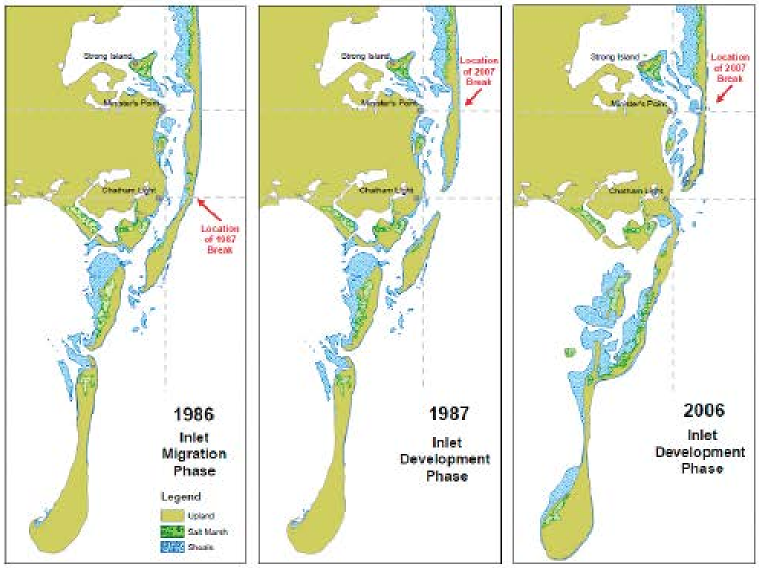

FIGURE 8 (a, b, c)

5. TIME SERIES OF MONOMOY CHANGES

The first two of the following three sub-sections present the results of cartographic and photographic research described in Section 3. The figures in *U.S Coast Survey Mapping* illustrate the general shape and position of the dominant landforms within the context of the surrounding shallow water features shown to a depth of 18 feet (3 fathoms) below mean low water. In contrast, the figures in *Aerial Photography* provide details of the changing landforms but little bathymetric information. In the third sub-section, *Discussion,* we call attention to the relationship between the landform changes and those of the surrounding bathymetry, as well as the distinction between the northern and southern sections of Monomoy.

<u>U.S. Coast Survey Mapping</u>.

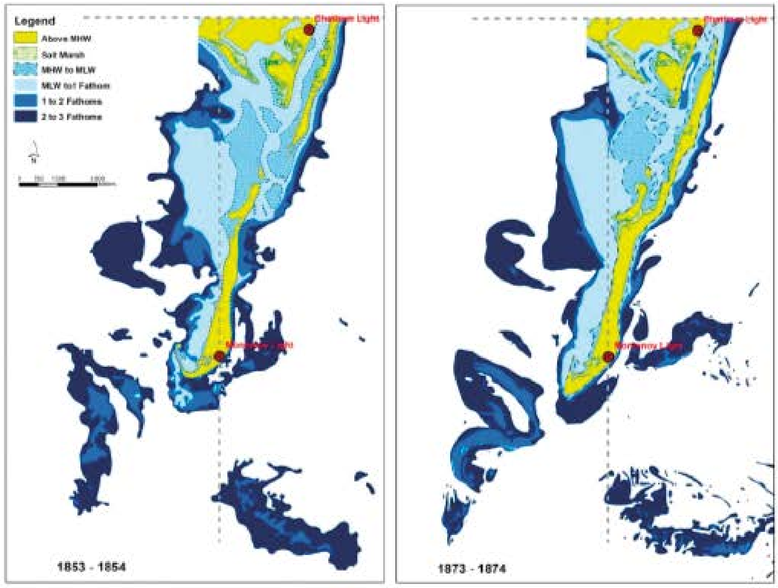

FIGURE 9 (a, b)

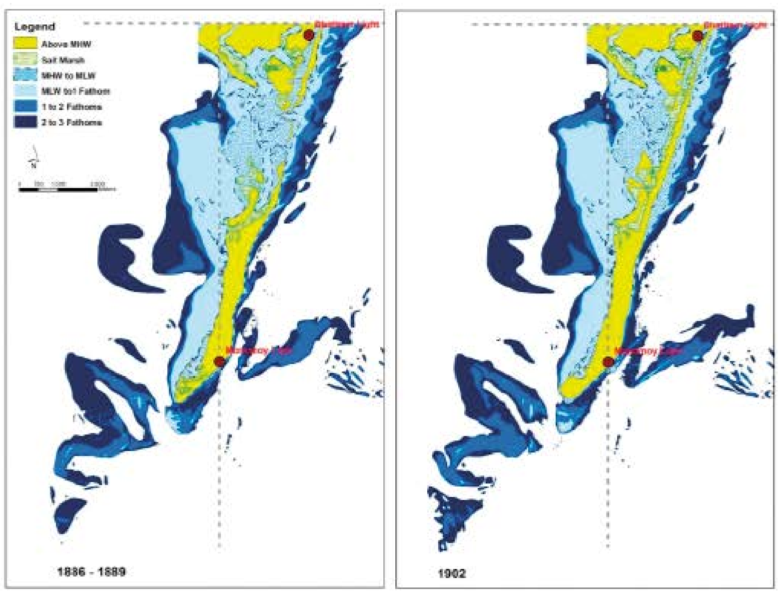

FIGURE 10 (a, b)

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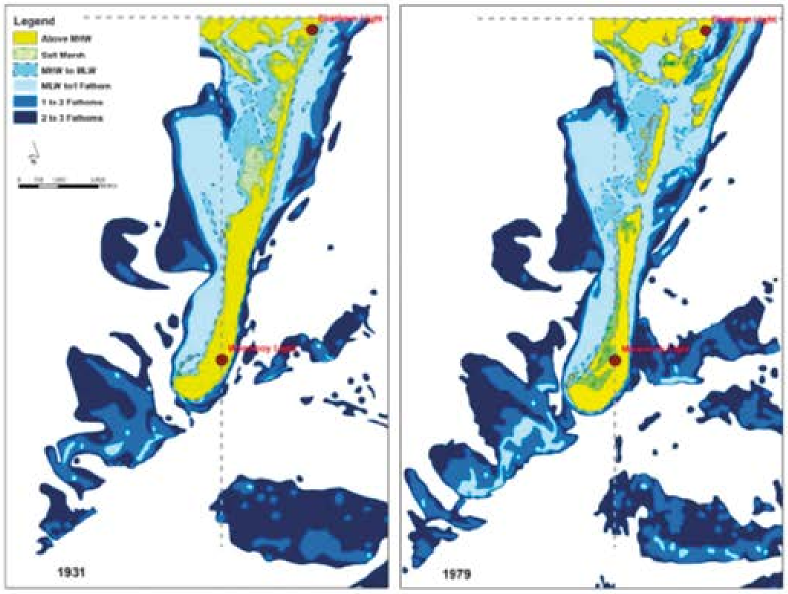

FIGURE 11 (a, b)

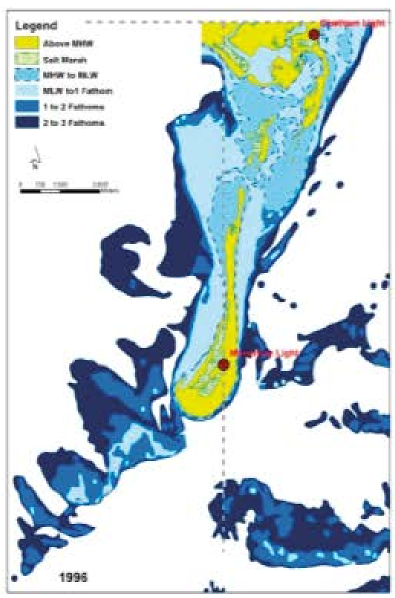

FIGURE 12

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Aerial Photography.

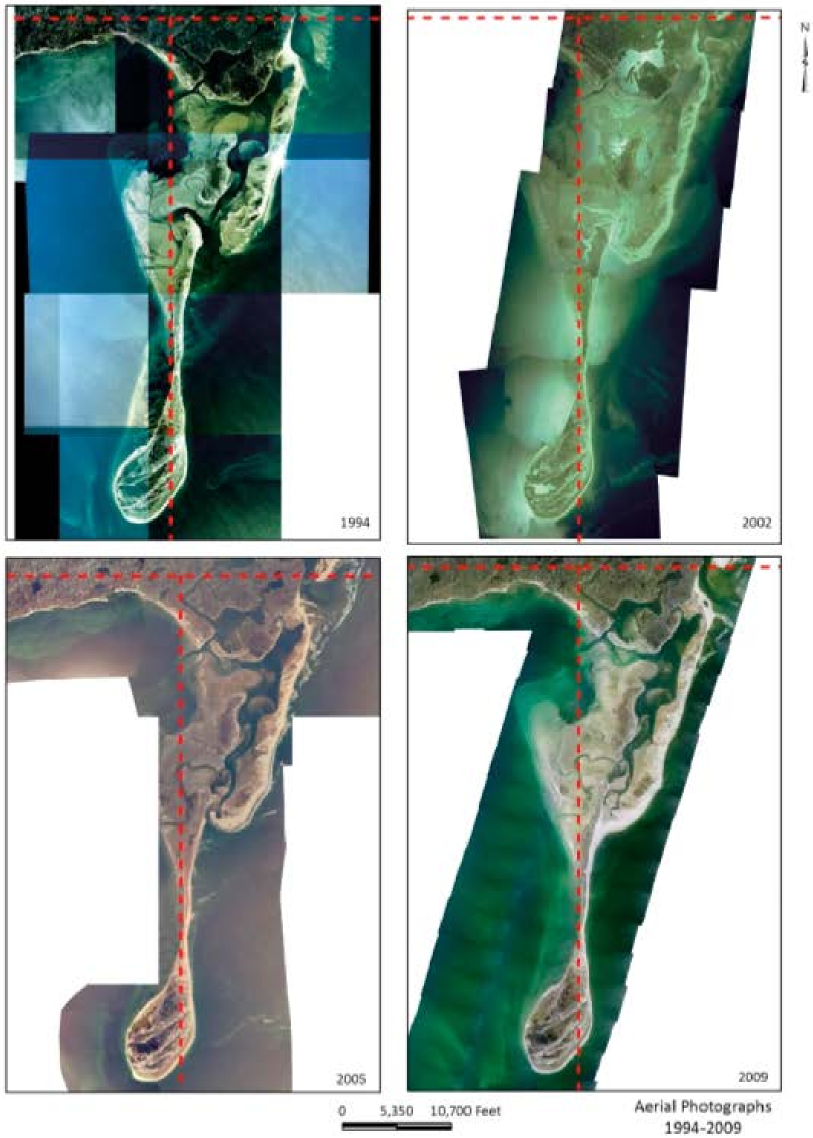

FIGURE 13

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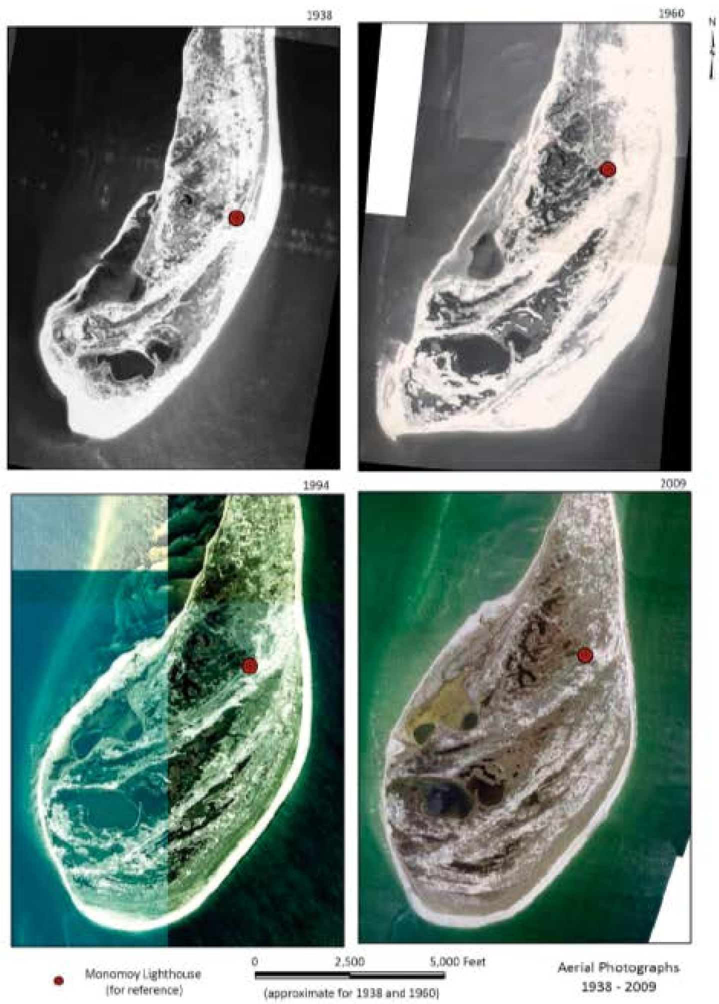

FIGURE 14

North Monomoy. Figures 9-12 reveal that Monomoy is comprised of two very distinct features. "North Monomoy" is a triangular shaped, mostly sub-tidal platform which widens northward. Subaerial landforms, when and where present, typically shift in position, size and shape. The margins of the North Monomoy Platform - well defined by the 6-foot (1 fathom) contour – appear remarkably similar in Figures 9-12 with the exception of Figure 9a, the earliest (1853-

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1854). It is likely that the somewhat irregular form of this figure's depth contours results from less accurate navigational techniques than those employed for the later surveys. The stability of the North Monomoy Platform is illustrated in Figure 15, which compares the location of the 6-foot contour in 1873-74 with its location in 1996. Both are superimposed on a 2009 photograph. The only apparent trend is on the western (Nantucket Sound) side, with a small retreat along the southwest-facing margin, and a small advance along the north-facing margin.

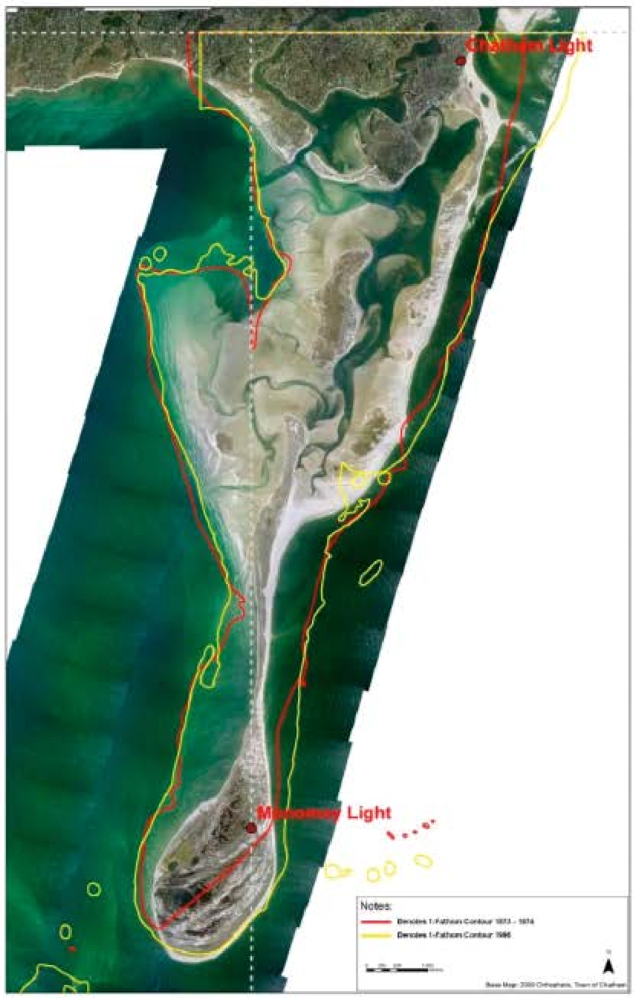

FIGURE 15

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Also apparent on Figures 9-12 is the mode of sediment transport from the eroding coast lying north of Monomoy (see Section 4), across North Monomoy Platform, to South Monomoy. A comparison of Figure 9 and Figure 5 illustrates the development of a second, more northerly tidal inlet in North Chatham that resulted in (1) closure of the inlet shown in Figure 9a, and (2) southward extension of the barrier spit to its north, leading to its welding onto South Monomoy (Figure 9b). Westward migration of the barrier across the platform is apparent in Figures 10a and b, leading to its eventual attachment to Morris Island (Figure 11a). At this stage, Monomoy was an unbroken peninsula connecting Monomoy Point to glacial upland in south Chatham.

This lasted only until southward extending Nauset Beach (Figures 6 and 7) reached the vicinity of Morris Island (Figure 11b) inhibiting wave-driven sediment transport along the Morris Island/North Monomoy coast. Deprived of a sediment supply, the peninsula broke down, first through a breach just south of Morris Island (1950's), then through a second breach (1978) (Figure 11b) separating North Monomoy from South Monomoy – each becoming a separate island. Tidal flow through the 1978 inlet produced a flood-tidal shoal near the western margin of the platform, which under the influence of the prevailing southwesterly wind waves, gave rise to the islet known as "Minimoy".

South Monomoy. "South Monomoy" is primarily a well-established and growing subaerial landform, consisting of dune, heathland, pond and marsh environments. It is a rare example of an actively accreting coastal landform along the exposed outer shore of Cape Cod, a distinction it shares only with the region near Race Point at the opposite extremity of the outer shore. Century-scale increase in area of the feature can be seen in the eastward and southward growth of the 6-foot (1 fathom) contour in Figure 15, and the southward extension of Monomoy Point since the mid-19th Century is clearly evident in Figures 9-12. Twentieth century change is shown in Figure 16 documenting a pattern of successive beach ridge development.

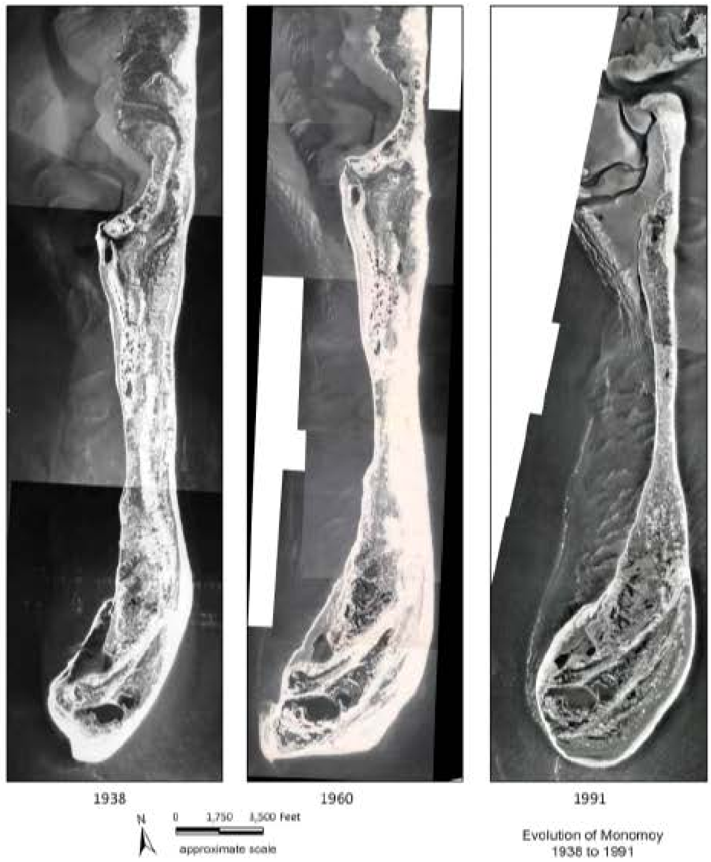

FIGURE 16

Change in location of the southern-most extremity of Monomoy Point is shown by the red vectors in Figure 17. The blue vectors in Figure 17 illustrate the change in location of the southern-most extremity of Handkerchief Shoal over the same time period. Evidently the evolution of South Monomoy is interdependent with that of Pollock Rip Channel and Handkerchief Shoal, which forms the channel's western boundary south of Butler Hole. Figure 18 shows historical locations of Monomoy Point for the years 1853, 1931, 1967, 1952 1979, and 1996, as defined by former ridge lines visible on the 2009 orthophoto.

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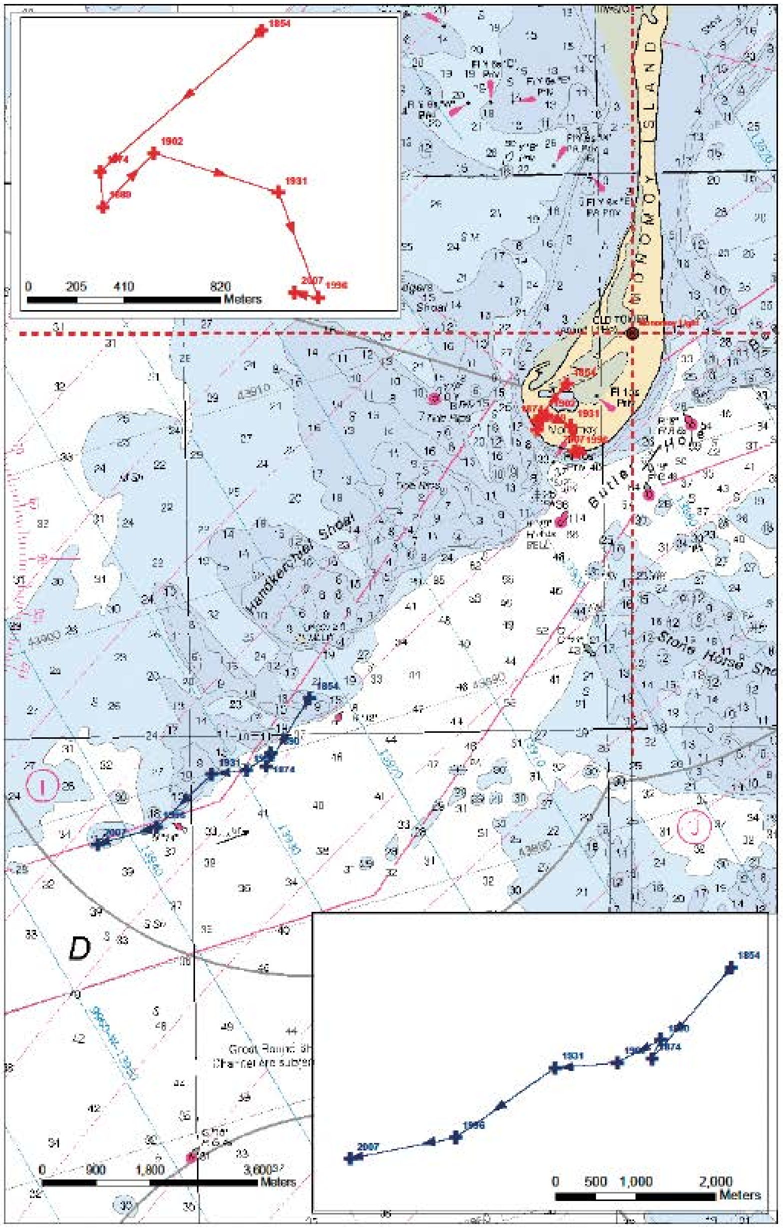
MONOMOY ISLAND
Handkerchief Shoal
Butler Hole
Stone Horse Shoal
OLD TOWER
D
0 205 410 820 Meters
0 900 1,800 3,600 Meters
0 500 1,000 2,000 Meters
1854
1874
1889
1902
1931
1996
2007

FIGURE 17

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FIGURE 18

It is interesting to note in Figures 9-12 that Monomoy Point appears to have grown southward directly onto an adjacent portion of Handkerchief Shoal, and that at present, for the first time,– it directly abuts on the margin of Butler Hole. However, the figures also indicate that

Handkerchief Shoal has developed considerably over the same time period. Together these observations suggest that future growth of Monomoy Point may follow a more southwesterly trajectory.

Figures 9 -12 also illustrate that some of the Nauset Beach-derived sediment that nourishes the growth of the eastern and southern South Monomoy continues around the point and forms the northward-trending spits that characterize the western shore of South Monomoy. The manner in which such spits develop into recurved spits that can eventually enclose ponds has been described by Zeigler, et al. (1965), who refer to Mitchell's (1886) account of the development of Powder Hole on South Monomoy:

> In my boyhood the Powder Hole was considered to be a very valuable harbor of refuge, but when I ran into it … in 1856, forty fishing vessels … packed it nearly full. Three fathoms at low water could be carried into this snug little place when our chart of 1854 was issued, but Mr. Chapin found but two feet at the time of his recent visit.

Wind waves from the southwest dominate sediment transport along the western coast of South Monomoy because of the extensive distance of fetch across Nantucket Sound. Winter prevailing northwesterly winds, in contrast, have a very limited fetch and, as a result, net sediment transport is directed to northward.

6. CLIMATE, SEA LEVEL AND 21st CENTURY MONOMOY

Small islands are particularly vulnerable to sea level rise (IPCC, 2007). However, this report shows that at the current rate of sea level rise, sediment supply from Nauset Beach to Monomoy is not only capable of maintaining the barrier complex, but of supporting ongoing accretion along the southern portion of South Monomoy Island.

Recent changes in global, or eustatic, sea level rise are largely driven by two phenomena: the thermal expansion of seawater as a result of increasing sea surface temperatures and the melting of glacial ice (Williams and Gutierrez, 2009). The most recent report of the Intergovernmental Panel on Climate Change (IPCC) predicted future rises in sea level of 0.18 – 0.59 m by the year 2100 (Fig. 19; IPCC, 2007). However, some more recent studies include higher contributions from melting ice and suggest a global sea level rise by 2100 of 1 m or more (Rahmstorf, 2007; Rahmstorf, et al., 2007; Vermeer and Rahmstorf, 2009).

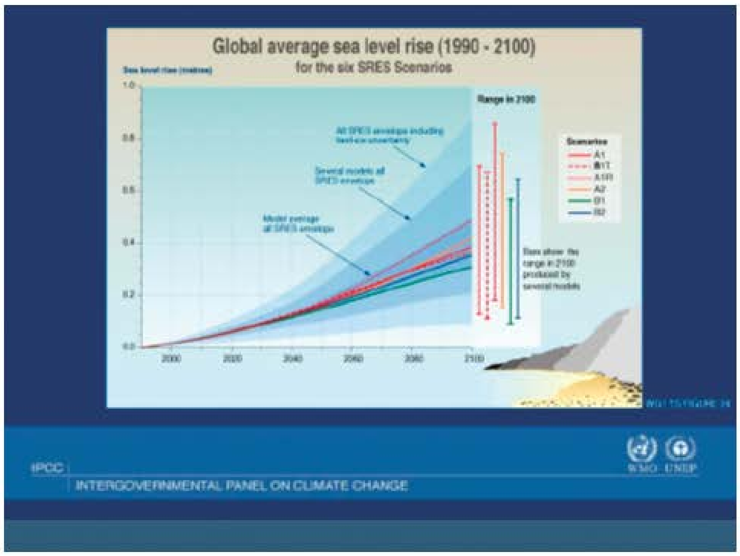

FIGURE 19

“Relative” sea level includes the augmentation or diminution by local phenomena on global sea level. Some of these phenomena include subsidence, post-glacial rebound, tectonic processes and oceanographic currents. For instance, in much of Scandinavia relative sea level is falling due to the rapid uplift of the land resulting from deglaciation since the Late Pleistocene.

Along the eastern seaboard of the U.S. researchers have identified a sea level trough maintained by the Gulf Stream and the North Atlantic Current that has kept the sea level anomalously low (Gregory, 2005; Meehl et al., 2007). Sea level in this area is 0.6 m lower than the global average and it has been shown that climate change will weaken those currents

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resulting in a relative sea level change in parts of the North Atlantic. Investigators modeled several scenarios for the eastern seaboard of the United States and demonstrated that if these currents are weakened relative sea level rise could increase between 0.15 – 0.21 m along the eastern seaboard, which would be superimposed upon the global sea level rise (Yin, et al., 2009).

During the 20th Century, relative sea level in southern New England rose at a long-term rate of about 2.6 – 3 mm/year (e.g., Fig. 20) or approximately 0.3 m (one foot) , and this represented an almost three-fold acceleration of the rate that the region had experienced for many centuries (Donnelly, 2004; Fig. 21).

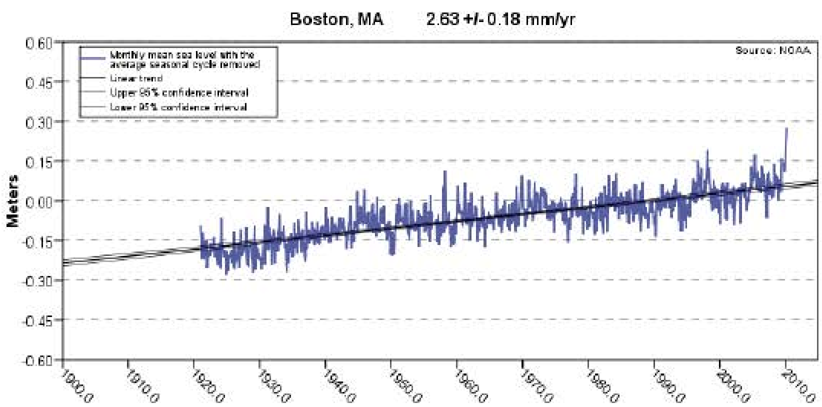

FIGURE 20

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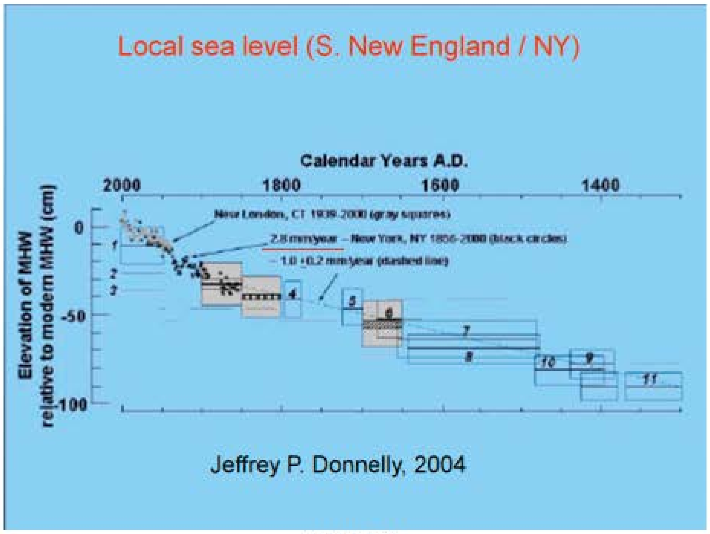

FIGURE 21

The global component of the southern New England 20th Century relative sea level rise of 0.3 m is close to the 0.18 m "low" IPCC estimate (IPCC, 2007) for the 21st Century. Therefore, under this scenario, we would expect 21st Century changes at Monomoy to follow the general patterns observed over the past century as follows:

During the 2nd and 3rd decades (2010-2030), South Beach overwashes more frequently producing washover fans on its inner (western) side; South Beach sediment moves southward along the South Monomoy outer shore; Monomoy Point grows southward/southwestward. In the 4th and 5th decades (2030-2050), South Beach overwashes thoughout its length; washover shoals reach Morris Island ending Outermost Harbor navigation; a re-curved spit, or hook, develops on southwestern side of Monomoy Point, sweeping northward. In the 3rd quarter-century (2050-2075), shoals from former South Beach end all "inside" navigation and finally connect Morris Island to South Monomoy; the Monomoy Point hook almost joins the western shore of South Monomoy. During the final quarter-century (2075-2100), Monomoy exists as peninsula for most of period, but thins south of Morris Island by close of century; Monomoy

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Point extends southwestward onto nearby section of Handkerchief Shoal; and an enclosed pond forms on western shore of South Monomoy inside former re-curved spit.

This scenario for the 21st Century assumes that the major forcing factors for the period will be similar to those of the recent past, but this assumption would not be valid if global sea levels rise a half-meter or meter or more by century-end. The magnitude of relative sea level rise in that eventuality would significantly modify a number of factors affecting the evolution Monomoy, such as regional wave climate, Nantucket Sound tides, and the elevation of the ground water table.

In such a case, the resulting increase in water depths over inner- and outer continental shelf shoals, including George's Bank, could increase ocean wave energy reaching Nauset Beach and Monomoy sufficiently to markedly increase southward net sediment transport – perhaps to the extent that Chatham upland south of Minister's Point becomes directly exposed to wave action (Giese, et al., 2009). In such a case, the large amount of sediment made available between the coast and upper shoreface (c. 10 m depth) could be sufficient to maintain a permanent barrier connection between Morris Island and South Monomoy.

A marked increase in Nantucket Sound water depths could increase tidal range and currents in the eastern sound, increasing the scour of Pollock Rip Channel – an erosional trough (Uchupi, et al., 1996) – thereby adding to the bulk of Handkerchief Shoal. This, in turn, coupled with an increased supply of sediment from the north, could enhance the southwestern growth of Monomoy Point.

A large and rapid relative sea level rise would be accompanied by a similar rise in the South Momonoy water table, flooding low-lying areas and enlarging existing ponds and wetlands. Prevailing southwesterly wind waves coupled with higher sea levels could markedly increase erosion of sound-side Monomoy, narrowing the peninsula. At the same time, higher sea levels and reduced sediment supply could be expected to deepen Monomoy Flats.

In summary, while the IPCC "low" global sea level rise projection might be expected to produce patterns of change over the 21st Century that are basically similar to those of the recent past, patterns accompanying the much higher sea level rise projections would be strikingly different. As stated above, there is a general consensus in the earth science community that global sea level rise rates are increasing and will continue to increase during the 21st Century, but there is much uncertainty regarding the magnitude of that increase within the ranges discussed. Accordingly, it seems reasonable to assume that the patterns of coastal change at Monomoy during the 21st Century will follow the general trends of those experienced over the recent past, but at an accelerated pace.

7. DREDGING

Bottom sediment dredging in the vicinity of Monomoy raises question with respect to the potential negative and positive impacts of this activity on the Sanctuary. Dredging in the region is not uncommon. The entrance channel to Stage Harbor, which lies north and west of Morris Island, is a federally maintained waterway and regularly dredged. In addition, the Town of Chatham dredges to maintain safe navigation of its waters for both commercial (especially fishing) and private vessels. Past history has shown these operations to be benign with respect to local environmental impacts on water quality (e.g., turbidity, nutrients, toxins), but the need for suitable sites for dredge spoil deposition has been recognized, and the possibility of depositing such sediment within the Sanctuary has been discussed.

Such biological questions as effects of dredging activities on benthic infauna are beyond the scope of this report, but potential impacts on the physical environment can be addressed within the context of its findings. Given the history of high-energy sediment transport at North Monomoy and Monomoy Flats, the addition of suitably-sized sediment there would not appear to present difficulties. Since the potential sediment volumes involved would be small in comparison to those contributed annually by natural processes, the major impact would be to slightly increase the rate of growth of the barrier complex.

However, the suggestion of using Stage Harbor dredge spoil to create an islet, similar to "Minimoy", that would provide a suitable environment for beach nesting birds raises several concerns. First, although a northerly location on Monomoy Flats would be preferred for economic reasons, it could have negative impacts on nearby navigation channels. Second, there is the question of the lifespan of such an islet. Unlike Minimoy, which developed slowly as a flood tidal shoal over an extended period under natural conditions, a single, quickly-deposited islet would soon be reworked by waves and tides, and lacking a extended source of additional sediment, could be transformed to an inter-tidal shoal sooner than expected.

A possible alternative plan could locate a Stage Harbor dredge spoil deposition site immediately adjacent to the western shore of North Monomoy. While not providing the advantages of a separate islet, such a deposit would increase the bird nesting area and could be could be designed to be compatible in form with the existing wave-dominated shoreline.

8. FUTURE RESEARCH

Coastal Change Monitoring. Historical data discussed in this report confirm earlier suggestions that evolution of the Monomoy barrier system is closely linked to that of the Nauset Beach barrier system. Since the formation in 1987 of a new tidal inlet (now known as "South Inlet") opposite Chatham Light, the Town of Chatham has been recording annual changes in Nauset Beach using high-resolution vertical aerial photography. It would be prudent for the Sanctuary to partner with Chatham in this effort, thereby by extending the annual coverage to include all of Monomoy. Interpretation of the resulting time series of photographic images would provide invaluable guidance for Sanctuary management decision-making.

Bathymetric Analysis. The historical bathymetric data depicted on the H-sheets of the U.S. Coast Survey and its successor agencies can be an important source of information for assessing large-scale and long term coastal change in response to natural processes and human activity. When used appropriately, comparisons of H-sheets prepared at different points in time can yield important insights into changes in regional sediment transport systems, estimates of sediment transport, and determinations of sediment budgets, which can in turn be used to study and predict geomorphic changes (Byrnes, 2002).

In order to achieve meaningful results from a comparative analysis, historical data must be translated accurately to a common, contemporary horizontal datum. Further, detailed analyses of the accuracies and uncertainties associated with the vertical data (soundings) must be conducted in order to assess the reliability of the comparative analysis for the calculation of sediment volumes. With uncertainties accounted for, these calculations may be used to quantify the net movement of sediment into and out of a study area and associated long-term net transport rates, to assess changes to sediment volumes, and to evaluate changes in nearshore bathymetry.

Recognizing the importance of the Monomoy Barrier Beach system to the local community and its significance as a coastal resource and habitat, further study of the system (beyond the scope of the current study) that incorporates a detailed and quantified assessment of historical bathymetric data depicted on the H-sheets would be an important contribution to contemporary coastal zone management decisions that will affect the long-term sustainability of areas such as the Monomoy Barrier Beach system.

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